Review of current knee biomechanical modeling techniques

Gusztáv FEKETE[1], Béla CSIZMADIA[2], Patrick DE BAETS[1],
Magd A. WAHAB[1]
Department of Mechanical Construction and Production, Labo Soete
Ghent University[1]
Department of Mechanics and Technical Drawing, Institute for Mechanics and Machinery
Szent István University[2]

Abstract

In this paper we are going to present an essential modification of an existing analytical model. The model creation normally starts with a simplified, less complex analytical model, where the phenomena can be easily interpreted, checked and controlled. If this model is available and valid – with its certain simplifications – then as a following step, it can be either extended by taking into account earlier neglected factors or a similar but more advanced computational model has to be created in order to broaden the investigated factors.
The accent will be set on a neglected factor, the moving center of gravity (COG), in this paper, and the obtained results will be compared with some external data from other authors.

Keywords

biomechanics, human knee, analytical model

1. Introduction

The applied tools in the biomechanical modeling begin with the use of mechanical-analytical models and involve MR techniques, computer-aided-design, multibody- or finite element simulations.
In order to investigate complex motions with such programs and methods, a well-based, reliable analytical model has to be created with adequate number of constrains and reasonable simplifications. To show the impact of the neglected factors in the models, a well-known motion, the deep-squat will be presented, examined and explained throughout the paper. Let us look at the analytical modeling part of the investigation.

2. Analytical model

In the relevant literature, the kinetics of deep-squat is investigated by mechanical models and test rigs. The most spread among the test rigs is the so-called Oxford type while so far the most typical approximation of the deep-squat is the mechanical model shown in Figure 1 (Cohen et al., 2001). In the figure, the flexion angle is denoted as α, L is the theoretical length of the femur and the body weight vector is denoted as $\boldsymbol{G}$.

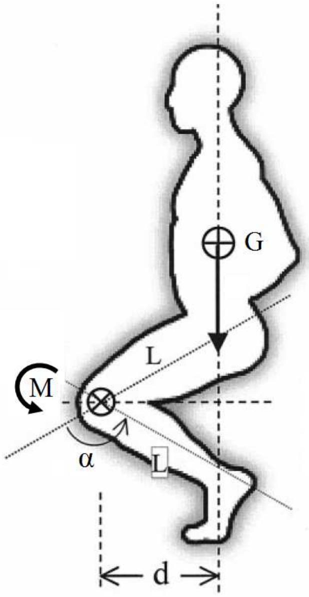

Figure 1. Deep-squat movement by Cohen et al.

The following simplifications were considered related to Cohen model:

- The model is quasi-static,
- Two-dimensional,
- The inertial forces during the movement are neglected,
- No internal forces ($\boldsymbol{F_s}$, $\boldsymbol{F_N}$) between the surfaces are considered,
- Only the squatting movement is investigated with the model,
- The load is derived from the mass of the person,
- The body weight vector ($\boldsymbol{G}$) can only move vertically.

There are three major forces which have significant effects in the knee joint, namely the quadriceps force ($\boldsymbol{F_q}$), the patellofemoral joint reaction force ($\boldsymbol{F_{pf}}$) and the patellar ligament force ($\boldsymbol{F_p}$) (see in Figure 2). Besides these forces there is one more important force the tibio-femoral force ($\boldsymbol{F_{tf}}$), but this force cannot be calculated with most of the analytical models.

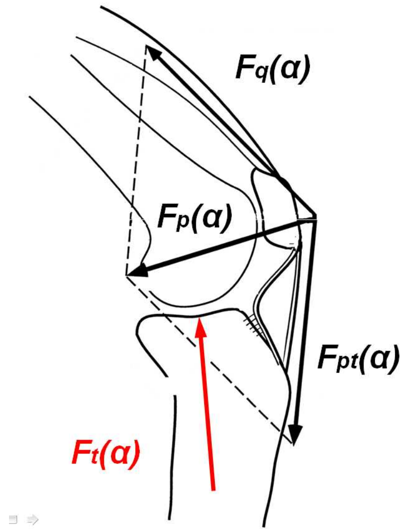

Figure 2. Free body diagram of the patellofemoral forces

Let us follow Cohen's approach in the derivation of the formulas according to Mason's description (Mason et al., 2008), thus let us note that *L* represents the length of the femur and the length itself is considered here as 0.45 m. The moment arm is represented as *d*, while the body weight vector as ***G***:

$$d(\alpha) = L \cdot \sin(\alpha / 2) \tag{1}$$

The so-called net-knee moment can be derived as follows:

$$M_k(\alpha) = 0.5 \cdot G \cdot d(\alpha) = 0.5 \cdot G \cdot L \cdot \sin(\alpha / 2) \tag{2}$$

The quadriceps force ($\boldsymbol{F_q}$) can be derived from the net knee moment (M_k) and the effective moment arm (see in Table 1) of the quadriceps (Salem and Powers, 2001):

$$F_q(\alpha) = \frac{M_k(\alpha)}{L_{eff}(\alpha)} \qquad (2)$$

The patellofemoral joint reaction force ($\boldsymbol{F_{pf}}$) can be expressed as a product of the quadriceps force and the *k(α)* dimensionless function (Van Eijden et al., 1986) which is found in Table 1:

$$F_{pf}(\alpha) = F_q(\alpha) \cdot k(\alpha) = \frac{M_k(\alpha)}{L_{eff}(\alpha)} \cdot k(\alpha) \tag{4}$$

Finally, the patellar ligament force (***F*$_p$**) can be derived by substituting Eq. (5) in Eq. (1), where *g(α)* dimensionless function (Van Eijden et al., 1986) which is found in Table 1.

$$F_p(\alpha) = F_q(\alpha) \cdot g(\alpha) = \frac{M_k(\alpha)}{L_{eff}(\alpha)} \cdot g(\alpha) \tag{5}$$

Thus the model is based on the assumption, that during the squat the center of gravity (shortly COG) – the body weight – does not change its line of action, thus the net knee moment can be derived as a simple function of the flexion angle. This approach assumes that the subject stays in perfectly vertical position during squatting which gives two false results. First, if a person tries to carry out a deep-squat movement, the balancing is completely necessary, which means that the COG has to change its place. Second, by neglecting the change of the COG calls forth unnecessary overestimation. The excursion of the COG has been described as a linear function of the flexion angle (Fekete et al., 2011), thus by inserting this function into the *L* length, the moment arm of the net-knee moment is reduced and the moving COG phenomena is taken into account. Let us consider the dimensionless λ_3 function (Table 1) which describes the change of COG (Fekete et al., 2011):

$$\lambda_3(\alpha) = -0.0022 \cdot \alpha + 0.86 \tag{6}$$

Then, let us create a new function for the *L* length:

$$L(\alpha) = L \cdot \lambda_3(\alpha) = -0.00099 + 0.387 \tag{7}$$

TABLE 1

Functions and constants of the mathematical model

	C0	**C1**	**C2**	**C3**	**C4**	**SD**	**r^2**	**Sample**	**p-value**
g(α) [-]	1.102	-2.209D-3	-1.493D-4	1.138D-6	0	0.1	0.989	13	$p < 0.05$
k(α) [-]	0.486	1.324D-2	-1.151D-4	+3.35D-7	0	0.11	0.989	13	$p < 0.05$
L_{eff}(α) [mm]	0.046	2.8D-4	-1.3D-5	8D-8	0	N/A	0.98	N/A	N/A
λ_3(α) [-]	0.86	-2.2D-3	0	0	0	0.2	0.63	31	$p < 0.05$

3. Results

With this altered length the net-knee moment is highly lowered as it follows:

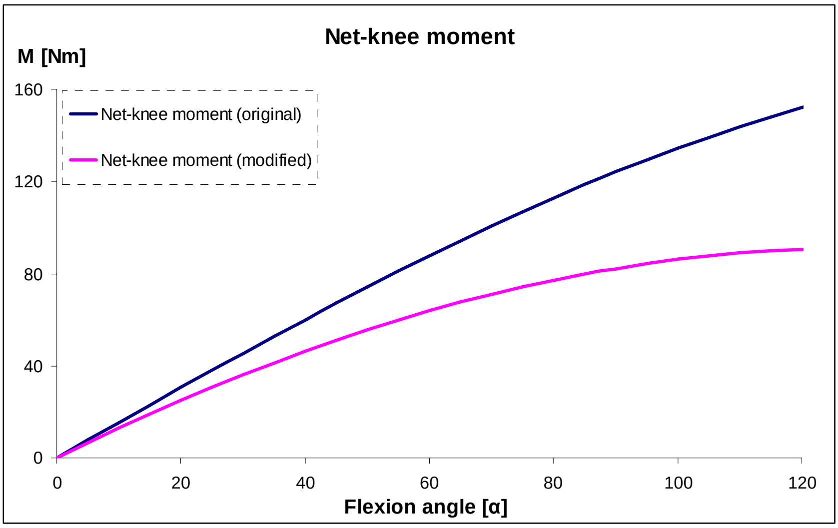

Figure 3. Net-knee moment functions

Naturally, all the other forces become lower than in the case of the original calculation method. In order to prove the validity of moving COG implementation, experimental data or other author's results are plotted along the results.

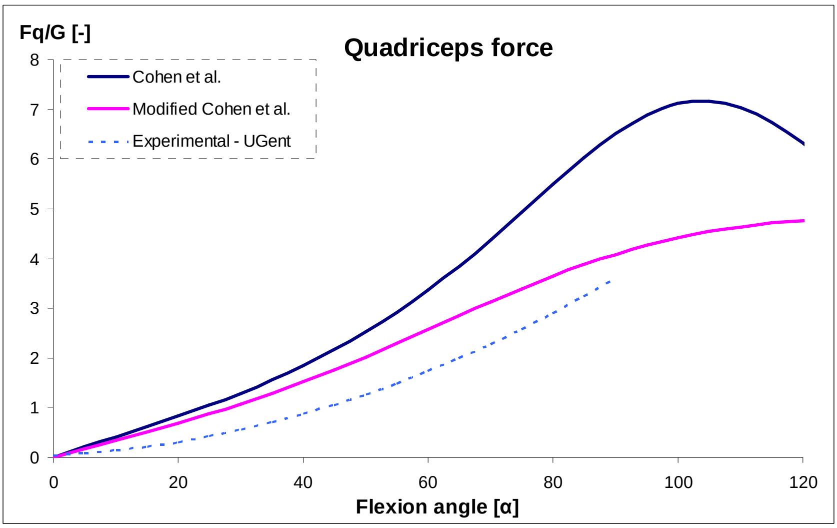

Figure 4. Quadriceps force function

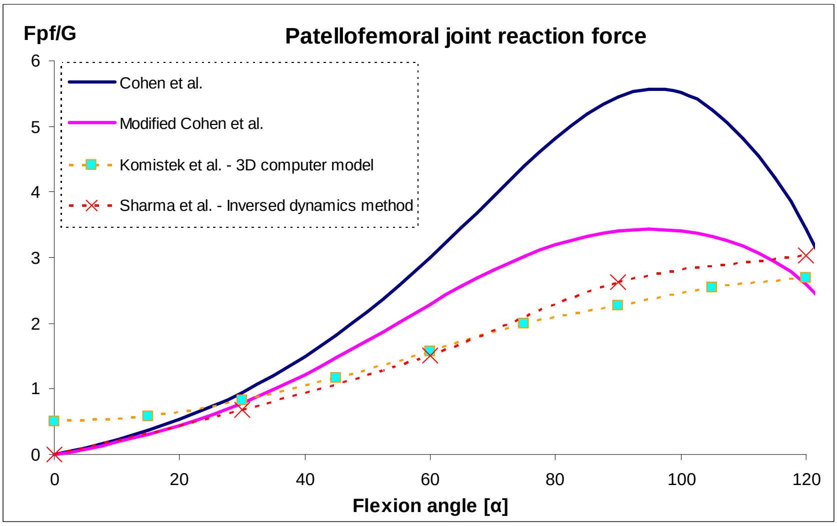

Figure 5. Patellofemoral joint reaction force

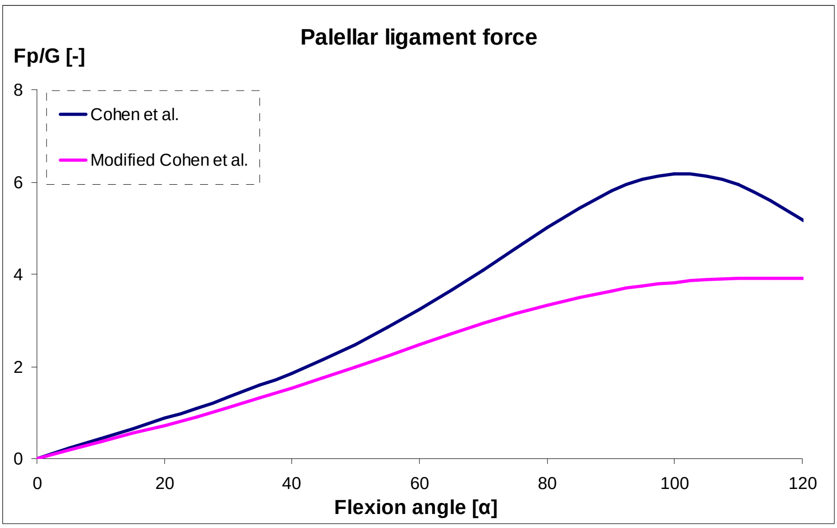

Figure 6. Patellar ligament force

The results obviously show that the modified model – with the moving COG – gives a better approximation (with less overestimation) contrarily the original method.

5. Conclusion

In summary, a novel modification of an existing model was presented. The moving COG has significant impact on the forces, and this was demonstrated in this paper. This analytical model was derived from theoretical assumptions and experimentally determined parameters – based on multiple human participants. The obtained, modified $\boldsymbol{F_q(\alpha)}$ force function can be extended for further use as an input function for isometric motion, since all the descriptive relationships found in the literature provide a ratio of the patellofemoral forces divided by the quadriceps force.

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